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Ice cores as an index of global volcanism from 1850 to the present

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Abstract. To evaluate an important cause of past climate change, climate researchers need reliable estimates of volcanic aerosol loading in the atmosphere. Previous indices, the dust veil index, volcanic explosivity index, and those by Mitchell (1970), Sato et al. (1993) and Khmelevtsov et al. (unpublished manuscript, 1993), all have drawbacks. Ice core acidity and sulfate records, because they contain physical evidence of atmospheric loading, are a promising source of information on past volcanic aerosols, but these records contain large nonvolcanic signals as well. We have compared northern hemisphere (NH) and southern hemisphere (SH) annual-average versions of five indices with eight NH and six SH ice core records for the period 1850 to the present in an attempt to identify the volcanic signal common to all records. The indices are all highly correlated with each other. For the NH, although the individual ice core records are, in general, not well correlated with each other or with any of the indices, a composite derived from averaging the cores, the ice core-volcano index (IVI), shows promise as a new index of volcanic aerosol loading. This new index correlates well with the existing non ice core volcanic indices and with high-frequency temperature records. For the SH the individual ice cores and indices are better correlated. The SH IVI is again highly correlated with all indices and individual ice cores but not with high-frequency temperature records. For both hemispheres the Southern Oscillation index shows no significant correlation with the volcanic indices, ice cores or the IVI, thus providing no evidence for the impact of volcanic eruptions on El Niño/Southern Oscillation events.

Introduction

Volcanism has long been implicated as a possible cause of weather and climate variations. Plutarch and others [*Forsyth*, 1988] pointed out that the eruption of Etna in 44 B.C. dimmed the Sun and caused crops to shrivel up in ancient Rome. Benjamin Franklin suggested that the Laki eruption in Iceland in 1783 might have been responsible for the abnormally cold winter of 1783-1784 [*Franklin*, 1784]. More recent work [e.g., *Robock*, 1979] has shown that volcanic aerosols can be important causes of temperature changes for several years following large eruptions and suggested that even on a 100-year timescale, they can be important when their cumulative effects are taken into account. Excellent reviews of the effects of volcanoes on climate include *Lamb* [1970], *Toon and Pollack* [1980], *Toon* [1982], *Ellsaesser* [1983], *Asaturov et al.* [1986], *Kondratyev* [1988], and *Robock* [1991]. Theoretical studies of the radiative effects include *Pollack et al.* [1976], *Harshvardhan* [1979], and *Hansen et al.* [1992].

Other possible forcings of climate change on the 100-year timescale include greenhouse gases, tropospheric aerosols, solar constant variations, atmosphere-ocean interactions, and random, stochastic variations. The problem of identifying a volcanic signal in the past is the same as the problem of identifying a greenhouse signal in the past, identifying a unique fingerprint of the forcing and separating out the effects of other potential forcings. Because the climatic signal of volcanic eruptions is of approximately the same amplitude as that of El Niño/Southern Oscillation (ENSO), because other sources of variability are of similar magnitude, and because there have been so few large eruptions in the past century, it is necessary to separate the volcanic signal from that of other simultaneous climatic variations. For several recent eruptions it has been demonstrated [*Angell*, 1988; *Nicholls*, 1988; *Mass and Portman*, 1989] that the ENSO signal in the past climatic record partially obscures the detection of the volcanic signal on a hemispheric annual average basis for surface air temperature. More recently, *Robock and Mao* [1992, 1995] have removed the ENSO signal in order to extract more clearly the seasonal and spatial patterns of the volcanic signal in surface temperature records. This observed signal matches the general cooling and northern hemisphere winter warming patterns found from general circulation model simulations [*Graf et al.*, 1993; *Robock and Liu*, 1994].

To evaluate the causes of climate change during the past century and a half of instrumental records or during the past 2000 years, including the medieval warming and the so-called "little ice age," a reliable record of the volcanic aerosol loading of the atmosphere is necessary. Five such indices have been compiled, based on different data sources and criteria. In the first part of the paper we describe each of these indices. Next we evaluate all the ice core acidity and sulfate records that are available for the period since 1850, which because they contain physical evidence of atmospheric loading are a promising source of information on past volcanic aerosols. As measures of past volcanism, these records also have problems, which we describe. Then we compare the volcanic indices and show that while they are all correlated with each other, they are all different, and it is difficult to tell which, if any, is a

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good measure of past volcanoes. We compare the ice core time series with each other and with the volcanic indices and show that ice core records are not well correlated with each other but when averaged together show a clear volcanic signal. Finally, we compare this new ice core volcanic index to measures of past climate change and show that short-term climate variations during the instrumental period have a measurable volcanic component.

Past Volcanic Indices

It has become clear in the last decade [e.g., *Rampino and Self,* 1984] that the effect of a volcano on climate is most directly related to the sulfur content of emissions that reach into the stratosphere and not to the explosivity of the eruption. These sulfur gases convert to small sulfate particles, which persist for several years in the stratosphere and efficiently scatter the incoming sunlight, reducing the direct and total solar radiation reaching the ground.

To investigate the effects of volcanic eruptions on climate, it would be desirable to have a volcanic index that is proportional to the physical effect of the volcanic dust veil on climate, namely, the net radiation deficit. If the index is incomplete in its geographical or temporal coverage, if it assumes that surface air temperature drops after an eruption and uses this information to create the index, or if it is a measure of some property of volcanic eruptions other than their long-term stratospheric dust loading, it will be unsuitable for this type of study. The timing of the index should be coincident with the atmospheric loading, not with the time of the initial atmospheric input or the subsequent surface deposition. All volcanic indices produced so far suffer from one or more of these problems.

Large explosive volcanic eruptions that are rich in SO_2 produce stratospheric H_2SO_4 aerosol layers that last for a few years, with an e-folding decay time of approximately 1 year. These sulfate aerosols are highly reflective and reduce the solar input to the climate system, producing a general cooling. In addition, the aerosols absorb terrestrial long-wave radiation, warming the stratosphere and influencing the winter circulation patterns [*Graf et al.*, 1993]. To determine the volcanic loading of the atmosphere, direct radiation measurements would be the best technique, and combinations of surface, aircraft, balloon, and satellite measurements have clearly quantified the distributions and optical properties of the aerosols from the 1982 El Chichón [*Robock*, 1983; special issue "Climatic Effects of the Eruption of El Chichón" in *Geophysical Research Letters, 10*, 989-1060, 1983] and 1991 Pinatubo [special issue "The Stratospheric and Climatic Effects of the 1991 Mount Pinatubo Eruption: An Initial Assessment" in *Geophysical Research Letters*, *19*, 149-218, 1992] eruptions.

In the past, however, such high quality measurements are lacking, and compilers of indices have had to use the available surface radiation measurements combined with indirect measures such as reports of red sunsets in diaries and paintings and geological evidence. Geological methods, based on examination of the deposits remaining on the ground from eruptions, can provide useful information on the total mass erupted and the date of the eruption, but estimates of the atmospheric sulfur loading, by what is called the petrologic method, are not very accurate. The petrologic method depends on the assumption that the difference in sulfur concentration between glass inclusions in the deposits near the volcano and the concentrations in the deposits themselves are representative of the total atmospheric sulfur injection but has been shown not to work well for recent eruptions for which we have atmospheric data [e.g., *Luhr et al.*, 1984].

For all the indices the problem of missing volcanoes and their associated dust veils becomes increasingly important the farther back in time they go. There may have been significant volcanic aerosol loadings during the time period of our study (1850 to present) that do not appear in any or most of the volcanic indices. Volcanoes only appear in most of the indices if there exists a report of the eruption from the ground. For recent eruptions, *Lamb* [1970] and *Sato et al.* [1993] used actual measurements of the radiative effects of the volcanic aerosols, and Lamb in addition used reports of atmospheric effects. Still, up to the present, all the indices may miss some southern hemisphere (SH) eruptions, as they may not be reported. Even in the 1980s the December 1981 aerosols from the eruption of Nyamuragira were observed with lidar but were reported as the "mystery cloud" for several years until the source was identified by reexamining the Total Ozone Mapping Spectrometer satellite record (A. Krueger, personal communication, 1988). Even as late as 1990, volcanic aerosols were observed with the Stratospheric Aerosol and Gas Experiment II satellite instrument, but it has not been possible to identify the source [*Yue et al.*, 1994]. Before 1978, with no satellite or lidar records, there may be important missing eruptions even in the NH averages. This problem does not exist for individual ice core records, because they are objective but not necessarily representative (see below) measures of volcanic sulfuric acid, except that the farther back in time one goes with ice cores, the fewer such records exist.

To compare the volcanic indices and the ice core data, we transform all series into annual and hemispheric averages. Table 1 lists five volcanic indices that have been compiled for the past. Each has its advantages, but each also has its problems, and they are described below. *Robock* [1981a] describes the first two in detail and *Robock* [1991] discusses the first three. This discussion is condensed and updated from those descriptions.

Lamb's Dust Veil Index

The first extensive modern compilation of past volcanic eruptions is the classic study of *Lamb* [1970], updated by *Lamb* [1977, 1983]. Lamb created a volcanic dust veil index (DVI), specifically designed for analyzing the effects of volcanoes on "surface weather, on lower and upper atmospheric temperatures, and on the large-scale wind circulation" [*Lamb*, 1970, p. 470]. *Robock* [1979] used Lamb's index to force an energy-balance model simulation of the little ice age, showing that volcanic aerosols played a major part in producing the cooling during that time period. The methods used to create the DVI are described by *Lamb* [1970], and in more detail by *Kelly and Sear* [1982], and include historical reports of eruptions, optical phenomena, radiation measurements (for the period 1883 onward), temperature information, and estimates of the volume of ejecta. In particular, he gave considerable weight to reports of red sunsets, such as the one portrayed in the famous 1893 Edvard Munch painting, "The Scream," which are caused by reflection of the setting Sun from the underside of stratospheric volcanic aerosol layers.

Lamb's DVI has been often criticized [e.g., *Bradley*, 1988] as having used climatic information in its derivation, thereby

Table 1. Volcanic Aerosol Indices

Name	Unit	How Calculated	Lag, year	Reference
DVI	Krakatau = 1000	*Sapper* [1917, 1927], sunsets, eruption and radiation observations	-1	*Lamb* [1970, 1977, 1983], updated
MITCH	aerosol mass	based on H. H. Lamb (personal communication, 1970)	0	*Mitchell* [1970], updated
VEI	Krakatau = 10^6	10^{VEI}, stratospheric diffusion model	0	*Newhall and Self* [1982], *Simkin et. al* [1981, 1984], T. Simkin (personal communication, 1993)
SATO	τ (λ = 0.55 μm)	*Mitchell* [1970], radiation and satellite observations	0	*Sato et al.* [1993]
KHM	τ (broadband)	radiation observations, petrologic method, and stratospheric diffusion model	0	S. S. Khmelevtsov et al. (personal communication, 1993)

DVI, dust veil index; VEI, volcanic explosivity index

resulting in circular reasoning if the DVI is used as an index to compare to temperature changes. In fact, for only a few eruptions between 1763 and 1882 was the northern hemisphere (NH) averaged DVI calculated based solely on temperature information, but for several in that period the DVI was calculated partially on the basis of temperature information. *Robock* [1981a] created a modified version of Lamb's DVI which excluded temperature information. When used to force a climate model, the results did not differ significantly from those using Lamb's original DVI, demonstrating that this is not a serious problem. Nevertheless, in this study we use that modified Lamb index, excluding any eruptions that appear solely because of temperature effects and eliminating the temperature influence on the DVI for the other eruptions.

Lamb's DVI is by definition an annual average, with 40% of the volcanic loading assigned to the year of the eruption, 30% to the next year, 20% to the next year, and 10% to the third year after the eruption. Lamb accounted for the latitude of the eruption, partitioned the volcanic aerosol into hemispheres, and provided tables of NH average loading for 1500-1982 [*Lamb*, 1970, p. 526; 1977, p. 66; 1983, p. 89] and SH average loading for 1890-1982 [*Lamb*, 1977, p. 66; 1983, p. 89]. We used these indices but used the detailed information in Appendix I of *Lamb* [1970] to eliminate the temperature influence and to construct a SH average for 1850-1889. We updated the indices to include estimates for the period from 1983 to 1995, accounting for the decay of the El Chichón cloud, the small 1986 Augustine eruption, and the 1991 eruptions of Pinatubo and Hudson. Since none of the ice cores include signals from these recent eruptions, this is mainly for completeness and comparison to the other indices. In Figures 1 and 2 we present the NH- and SH-average, annual-average time series of DVI from 1850.

Mitchell Index

Mitchell [1970] also produced a time series of volcanic eruptions for the period 1850-1968 using data from Lamb. As discussed by *Robock* [1978, 1981a] and *Sato et al.* [1993], the Mitchell volcanic compilation for the NH is more detailed than Lamb's, because Lamb excluded all volcanoes with DVI < 100 in producing his NH annual average DVI. Mitchell provided a table of the order of magnitude of total mass ejected from each volcano, which is a classification similar to the volcanic explosivity index (VEI). Mitchell assumed that 1% of the mass from each eruption formed a stratospheric aerosol layer and that it had a mean residence time of 14 months, similar to the assumption we made for our VEI index below, especially if you include the 2 months for the formation of the sulfuric acid particles. We used the same method as described below for the VEI to calculate hemispheric-average, annual-average time series for each hemisphere. In Figures 1 and 2 we present the NH- and SH-average, annual-average time series of Mitchell's aerosol mass from 1850, estimating the values for the recent eruptions.

Volcanic Explosivity Index

More recently, a comprehensive survey of past volcanic eruptions [*Simkin et al.*, 1981] produced a tabulation of the VEI [*Newhall and Self*, 1982] for all known eruptions, which gives a geologically based measure of the power of the volcanic explosion. This index has been used in many studies [see *Robock*, 1991] as an index of the climatological impact of volcanoes without any modification. A careful reading of *Newhall and Self* [1982], however, will find the following quotes: "We have restricted ourselves to consideration of volcanological data (no atmospheric data)..." and "Since the abundance of sulfate aerosol is important in climate problems, VEIs must be combined with a compositional factor before use in such studies." In their Table 1 they list criteria for estimating the VEI in "decreasing order of reliability," and the very last criterion out of 11 is "stratospheric injection." For VEI of 3, this is listed as "possible," for 4 "definite," and for 5 and larger "significant." If one attempts to work backward and use a geologically determined VEI to give a measure of stratospheric injection, serious errors can result. Not only is this the least reliable criterion for assigning a VEI but it was never intended as a description of the eruption which had a VEI assigned from more reliable evidence.

It has been the general consensus until now that because VEI is a geological measure of the explosivity of eruptions and not of the sulfate input to the stratosphere, its usefulness as an index of the effect of volcanic eruptions on climate is limited. For example, it was pointed out by *Robock* [1991] that while eruptions with a high VEI, such as Tambora (1815, VEI = 7) or Krakatau (1883, VEI = 6), may also have a large stratospheric impact, three recent examples demonstrate the

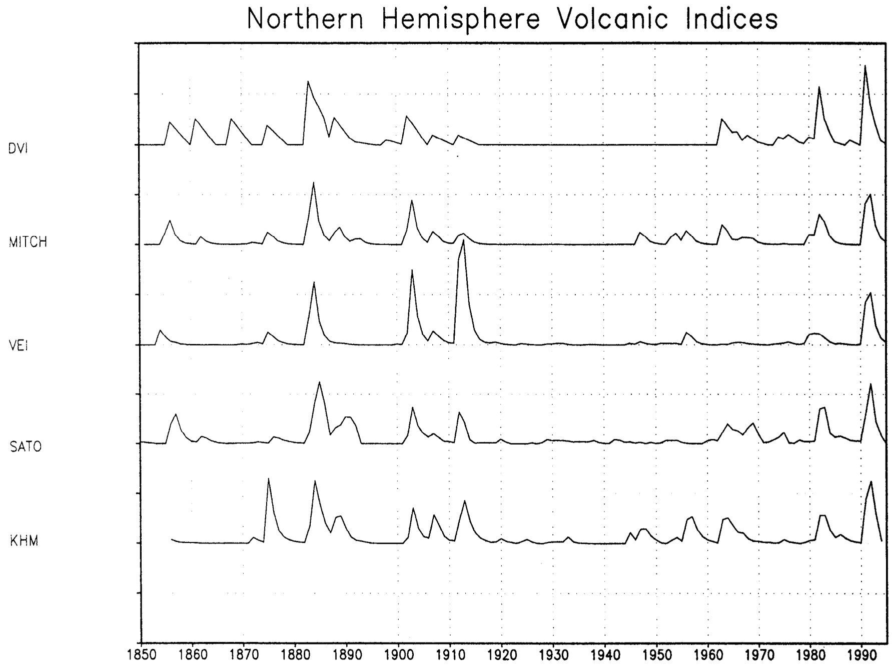

Figure 1. Northern hemisphere average volcanic indices (Table 1), expressed as optical depth (τ) at $\lambda = 0.55$ μm, with all but KHM normalized to the values of SATO for the Krakatau peak in the mid-1880s. The spacing between the zero lines of the curves corresponds to an optical depth interval of 0.2. The tick marks and horizontal grid lines are at an optical depth interval of 0.1.

danger in using the VEI for climate studies. Mount St. Helens in 1980 had a high VEI of 5, and while it had a large local temperature impact [*Robock and Mass*, 1982; *Mass and Robock*, 1982], it had a negligible stratospheric impact [*Robock*, 1981b]. Agung in 1963 and El Chichón in 1982, on the other hand, had a very large stratospheric impact [*Robock*, 1983] but a smaller VEI of 4, although El Chichón has since been assigned a VEI value of 5 based on more recent evidence (T. Simkin, personal communication, 1993). Several studies [see *Robock,* 1991] have been done using the VEI as an index for the climatic effect of volcanoes and then excluded Mount St. Helens as a special case. This example raised the question of the possibility of other special cases in the past for which we do not have the same additional information.

In spite of the above limitations we decided to evaluate VEI as a volcanic index by comparing it with the other indices and with ice core data. The raw VEI data are given as a value for each eruption at the time of the eruption but are not presented

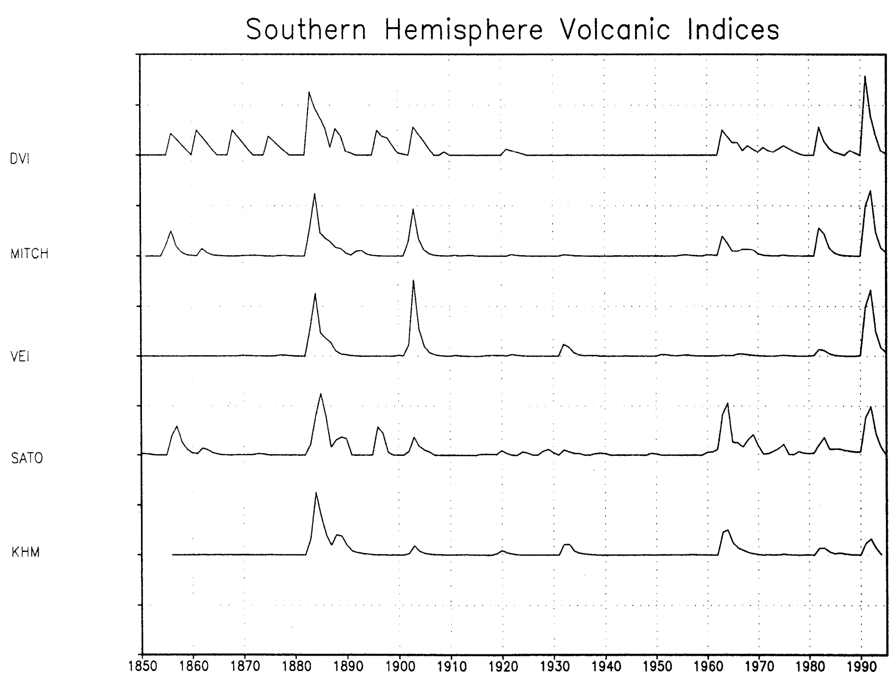

Figure 2. Same as Figure 1, but for southern hemisphere.

in a format to represent the spatial and temporal extent of the resulting stratospheric cloud. Because the VEI is a logarithmic measure of the power of volcanic eruptions, *Schönwiese* [1988] created a Smithsonian volcanic index (SVI) which takes 10 to the VEI power and included volcanic eruptions with VEI of 3 and greater in his analysis of the climatic effects. While eruptions of VEI 4 and smaller would not be likely, in general, to have a large climatic impact, the SVI would not give them much weight anyway. To create hemispheric and annual average time series, we used the SVI approach, including only eruptions with VEI ≥ 4. We assumed that eruptions within 30° of latitude of the equator contributed half of the aerosol to each hemisphere and those poleward of 30° contributed only to the hemisphere of the eruption. We assumed that it took 2 months after each eruption for the aerosols to form from their original SO_2 gas and to move into their respective hemispheres, and then that the concentration decayed exponentially with a 12-month e-folding time. From these monthly values summed for each hemisphere from the 68 eruptions since 1851, we then averaged over each year to get the resulting time series, which are shown in Figures 1 and 2.

Sato Index

Sato et al. [1993] produced NH- and SH-average indices for each month. We obtained them electronically, as described in their paper, and show annual-average values in Figures 1 and 2. Their index, expressed as optical depth at wavelength 0.55 μm, is based on volcanological information about the volume of ejecta from *Mitchell* [1970] from 1850 to 1882, on optical extinction data after 1882 and on satellite data starting in 1979. The seasonal and latitudinal distributions for the beginning of the record are uniform and offer no advantages over the DVI and, in fact, show less detail than the latitudinally dependent index of *Robock* [1981a], who distributed the aerosols in latitude with a simple diffusive model. The more recent part of the record would presumably be more accurate than the DVI or VEI, as it includes actual observations of the latitudinal and temporal extent of the aerosol clouds. For example, for recent tropical volcanic eruptions, such as Agung (8°S) in 1963, their index shows that most of the aerosols stayed in the SH and for El Chichón (17°N) in 1982, most of the aerosols stayed in the NH.

Khmelevtsov Index

S. S. Khmelevtsov et al. (personal communication, 1993) used petrologic estimates of the output of historic volcanoes, combined with a two-dimensional stratospheric transport and radiation model, to produce monthly average latitudinal distributions of the broadband visible optical depth and other optical properties of the stratospheric aerosol loading during the period 1850-1992. This index depends on the accuracy of the petrologic estimates but has the most sophisticated radiation calculation. We averaged the optical depth data with the appropriate area weighting to get hemispheric, annual averages, and show them in Figures 1 and 2.

Ice Core Time Series

The sulfate aerosols from volcanic stratospheric clouds settle into the troposphere after each eruption. Deposition from nearby volcanoes begins immediately after the eruption, and that from distant volcanoes can continue for 2-4 years after the eruption. Some aerosols reach the surface in precipitation or by dry deposition over glaciers and ice caps and are preserved in the snow and ice. Measurements of the total acidity or actual sulfate content in the ice potentially allow the computation of the volcanic contribution, with high precision in the timing. Several papers have called for a volcanic index based on ice core data, such as the glaciological volcanic index proposal of *Legrand and Delmas* [1987]. There are several potential problems with using these measurements as an objective measure of the atmospheric loading from volcanic eruptions, however. Before we compare the different ice core records, we discuss the measurement techniques and the potential problems of using them as volcanic indices.

Measures of the Volcanic Content of Ice

Several different methods are used to measure the chemical content of snow and ice that give information about volcanic aerosol deposition. Acidity can be inferred by measuring the electrical conductivity of the solid ice, either by passing a direct current through the ice (the electrical conductivity method (ECM)) or by dielectric profiling (DEP) using alternating current. Investigators have also measured the conductivity of melted glacial ice. Acid titration is a fourth method of determining the hydrogen ion concentration, and is generally the best method for measuring acidity, as long as the melt has not been contaminated in the lab, by NH_3, for example (J. C. Moore, personal communication, 1994). If a chemical analysis of all the major anions and cations is made, the acidity can be inferred by the difference between the charges.

Direct measurements of sulfate ion content can also be made. Total sulfate measurements include sodium sulfate derived from sea salt, which is customarily removed from the data by subtracting a fraction of the total sodium ion concentration that reflects the ratio of $NaSO_4$ to NaCl in seawater. The resulting quantity is non-sea-salt sulfate (NSS SO_4) or "excess sulfate." The data we used include several of these types of measurements.

When comparing different ice cores, the different types of volcanic measures must be considered. Direct measure of sulfates have the advantage, as compared to acidity measurements, that sulfates are the material in the stratospheric aerosols, and acidity measurements are contaminated with other acids. Furthermore, dielectric profiling responds to ammonium variations which are unrelated to volcanism [*Moore et al.*, 1994]. Sulfates, however, also have nonvolcanic sources, as discussed below, so the optimal ice core measure of volcanic aerosol loading is not obvious a priori.

In the Arctic and low latitudes the snowfall rate is great enough to produce layers with an annual cycle of $\delta^{18}O$. This allows the counting of the annual layers, with the potential for exact dating of each layer. In central Antarctica the snowfall rate is insufficient to produce countable annual layers [e.g., *Legrand and Delmas*, 1987]. Therefore, the usual method is to establish a well-dated layer as a marker, such as the Krakatau or Tambora layer or a layer of radioactive fallout from atmospheric atom bomb tests, and then to linearly extrapolate the time as a constant function of depth. The Siple data, however, are from the Antarctic peninsula which had sufficient snowfall for layer counting [*Mosley-Thompson et al.*, 1991]. The time series we used had time resolution from 8 to 10 measurements per year (20D) to one measurement every 2 years (GISP2). We converted those not presented as annual averages to annual averages by averaging or interpolating.

Ice Core Time Series

Table 2 presents the eight NH, one tropical and five SH ice core time series used in this study. From a review of the published literature we selected all cores for which acidity or sulfate ion data were available with annual or better resolution for the time period 1850 to 1960 or later, or which provided all the volcanic peaks during that time period. Two ice core records with shorter time periods and one core with biennial resolution were also included. In addition, we obtained unpublished data for the Summit and Siple Station cores. Most of the time series were presented to us by the people that drilled the cores and initially analyzed them, and we are grateful to them. The GISP2 core had already been partially analyzed, and we received the detrended time series. Table 2 also lists the locations of the cores, the type of measurement and units, the sources of our time series, and the dates included in this analysis.

Although other ice cores exist, most do not have sufficiently detailed temporal resolution for our purposes or do not cover the time period we are interested in. We did not include data from Mizuho station in Antarctica because the dating was not considered reliable [*Fujii and Watanabe*, 1988]. We also did not include data from mid-latitude or tropical glaciers other than Quelccaya because these records are contaminated by large amounts of alkaline dust from nearby deserts or anthropogenic sources [*Wake et al.*, 1990; *Wagenbach*, 1989; *Thompson et al.*, 1990]. We included Quelccaya because we wanted to test this hypothesis, even though we did not expect to find a volcanic signal (E. Mosley-Thompson, personal communication, 1992). If sulfate measurements from tropical ice cores existed rather than acidity measurements, the alkaline dust (other than $CaSO_4$) would not affect them and they might be an important source of information about global volcanism.

Some of the ice core papers specifically identified volcanic signals in their records, but there was no consistency in these identifications. Each paper identifies a different set of eruptions, even from two cores only 5 km apart [*Delmas et al.*, 1992]. For these two cores we used a time series of just the volcanic peaks, as the background values were not given. For all the other ice cores we extracted the volcanic signals in a consistent way, as described below.

Figures 3 and 4 show each of the NH and SH ice core time series. One is immediately struck by the large differences between these time series, even between time series from nearby locations. Some show long-term trends not shown by others. The signal of a volcanic eruption would be a large peak with a duration of 1-2 years. Although some appear to have similar peaks, there are many peaks that do not appear in other time series. Why are they so different? Can they be used to provide information about stratospheric volcanic aerosol loading? Is one correct and all the others wrong? Before applying statistical adjustments to the time series and objectively measuring their correspondence with each other and the previous volcanic indices shown in Figures 1 and 2, we present some reasons why they might not be expected to agree.

Problems in Using Ice Core Time Series As Measures of Volcanic Aerosol Loading

The potential problems in relating measures of acidity or sulfate in ice cores to the stratospheric volcanic aerosol loading can be classified into at least eight different categories.

Other Sources of Acids and Bases

Because acidity reflects HNO_3 and HCl as well as H_2SO_4, not all acidity maxima are related to maxima in sulfate aerosols. The amount of nonvolcanic acids in ice cores varies considerably on interannual scales, complicating the process of isolating volcanic signals. (The problem of other sources of sulfates is discussed next.) Acidity also reflects the deposition of alkaline dust, and variations of alkaline dust deposition can affect the acidity measurements by neutralizing the acid, even if deposition from all acids does not change. Ammonium spikes (possibly from biomass burning events) produce minima in ECM measurements due to neutralization [*Taylor et al.*, 1992], while they produce DEP maxima due to their electrical effects [*Moore et al.*, 1994]. Multivariate measurements from ice cores, in which all species are measured chemically, would help to eliminate this problem and have been made for a few specific cases [e.g., *Taylor et al.*, 1992], but due to the other problems listed below, this still might not produce a better volcanic index.

Other Sources of Sulfate

Using sulfate measurements eliminates the source of error from other acids and bases, but other nonvolcanic anthropogenic and biogenic sulfate sources exist that can obscure the volcanic signal by producing a varying background level of sulfate and adding to the noise of the record. The most serious problem is the increasing anthropogenic sulfate loading of the NH troposphere which is reflected in large increasing trends in some but not all of the NH ice cores. *Neftel et al.* [1985] claim that anthropogenic sulfate has risen over the past century to the point that it effectively obscures the volcanic signal, but this would depend on the relative amount of anthropogenic and volcanic deposits. In our analysis, described in the next section, we remove these trends in order to examine the relative increase of sulfate in peaks that could be attributed to volcanoes. Large eruptions should produce peaks of 1 or 2 years far above the anthropogenic background.

Different cores may contain different concentrations of anthropogenic sulfate, depending on their altitude, distance, and horizontal location relative to the trajectories from the industrial sources. At Dye 3 and Summit in recent years, *Jaffrezo et al.* [1994] found low concentrations of sulfate in winter air and suggested that "Arctic haze" is not present that far south in this season, although the high altitude of these stations would probably place them above the boundary layer most of the time. In other seasons they suggested that sporadic transport of anthropogenic sulfate aerosols occurred between longer periods of low sulfate concentration. At Alert on the Arctic Ocean, in contrast, air measurements show sulfur peaks in winter-spring (January to April) related to anthropogenic Arctic haze, and a minimum in summer due to weak northwest transport and heavier precipitation [*Barrie*, 1986; *Li et al.*, 1993].

Biogenic sulfate may also be a source of noise in ice core records. Recent analysis of methanesulphonate concentrations indicates that some of the peaks in the South Greenland 20D core may be biogenic in origin and that biogenic sulfur may have accounted for 50% of total sulfur deposition before 1900, but only about 20% at present [*Whung et al.*, 1994]. Biogenic sulfate has spring and summer peaks apparently related to biological productivity levels in the North Atlantic and Arctic Oceans.

Table 2. Ice Core Time Series

Series	Latitude	Location	Period	Source	Measure Type	Units	Lag, year	Reference
A84	81°N	Ellesmere Island, Canada	1850-1961	authors	ECM	μA	0	*Fisher and Koerner* [1988, 1994]
A81	81°N	Ellesmere Island, Canada	1912-1980	paper	ECM	μS/m	0	*Barrie et al.* [1985]
GISP2	73°N	Central Greenland	1850-1984	authors	NSS SO_4	μequiv./l	-1	*Mayewski et al.* [1993a], *Zielinski et al.* [1994]
Summit Core 2	72°N	Central Greenland	1850-1989	author	NSS SO_4	μequiv./l	-1	E. Mosley-Thompson (personal communication, 1993)
Crête Index	71°N	Central Greenland	1850-1972	author (via Matossian)	$[H^+]$	μequiv./kg	0	*Hammer* [1977], *Hammer et al.* [1980]
Dye 3	65°N	Southern Greenland	1895-1977	paper	NSS SO_4	ng/g	0	*Neftel et al.* [1985]
20D	65°N	Southern Greenland	1850-1983	authors	NSS SO_4	ng/g	0	*Mayewski et al.* [1990]
Mount Logan	61°N	Mount Logan, Yukon	1850-1979	authors	total SO_4	μequiv./l	0	*Mayewski et al.* [1993a]
Quelccaya	14°S	Peru (Andes)	1850-1983	NSIDC	ECM	μS/m	0	*Thompson et al.* [1986]
G15	71°S	East Dronning Maud Land	1850-1983	authors	DEP	μS/m	-1	*Moore et al.* [1991]
Dome C	75°S	Antarctica	1850-1973	paper	NSS SO_4	μequiv./l	+1	*Legrand and Delmas* [1987]
Siple	76°S	Antarctic Peninsula	1850-1983	author	NSS SO_4	μequiv./l	0	E. Mosley-Thompson (personal communication, 1993)
PS1	90°S	South pole	1850-1984	paper	NSS SO_4	ng/g	0	*Delmas et al.* [1992]
PS14	90°S	South pole	1850-1984	paper	NSS SO_4	ng/g	0	*Delmas et al.* [1992]

NSIDC, NOAA National Snow and Ice Data Center; ECM, electrical conductivity measurement; author(s), provided to us in digital form by the author(s) of the paper; NSS SO_4, non-sea-salt sulfate; paper, digitized by us from figure in paper; DEP, dielectric profiling

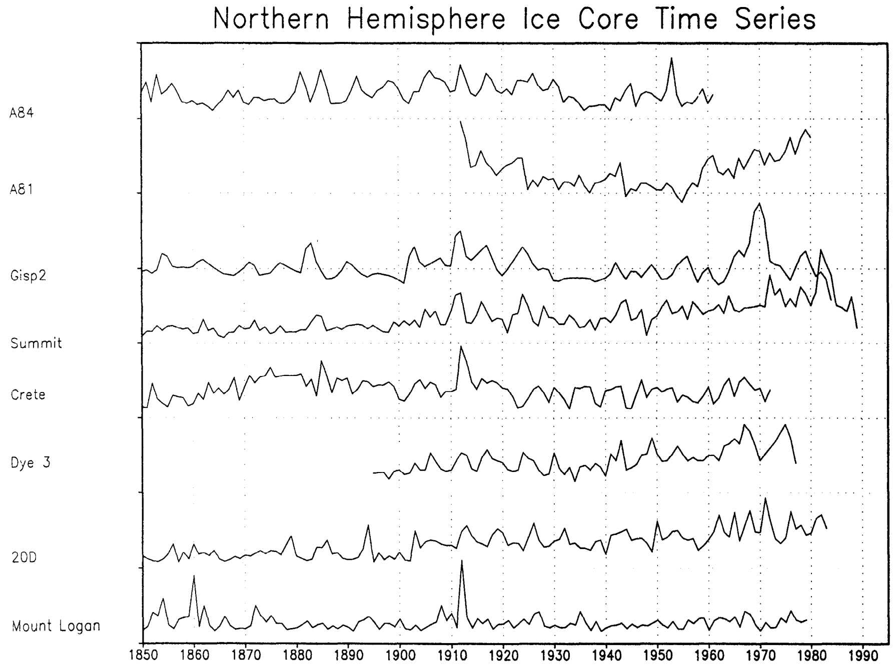

Figure 3. Northern hemisphere ice core time series. The GISP2 record was already detrended when we received it. See Table 2 for details about each series and units. All curves were adjusted to the same standard deviations.

Dating

The dating of ice cores is subject to considerable uncertainty in some cases, especially in low-accumulation areas. Most of the ice cores (see references in Table 2) claim an absolute accuracy of ±1 year. In the Arctic and low latitudes the snowfall rate is great enough to count annual layers, but errors can occur due to missing or false extra layers. The peaks associated with major eruptions do not occur in exactly the same years in series from the same areas, suggesting that the dating is not completely consistent. For example, different Greenland records show peaks from Mount Katmai at 1911, 1912, and 1913 (Figure 3).

In some areas of Antarctica the snowfall rate is insufficient to produce countable annual layers. Therefore the usual method, to establish a well-dated layer as a marker and linearly extrapolate the time as a constant function of depth, can produce large errors as the snowfall rate changes over time.

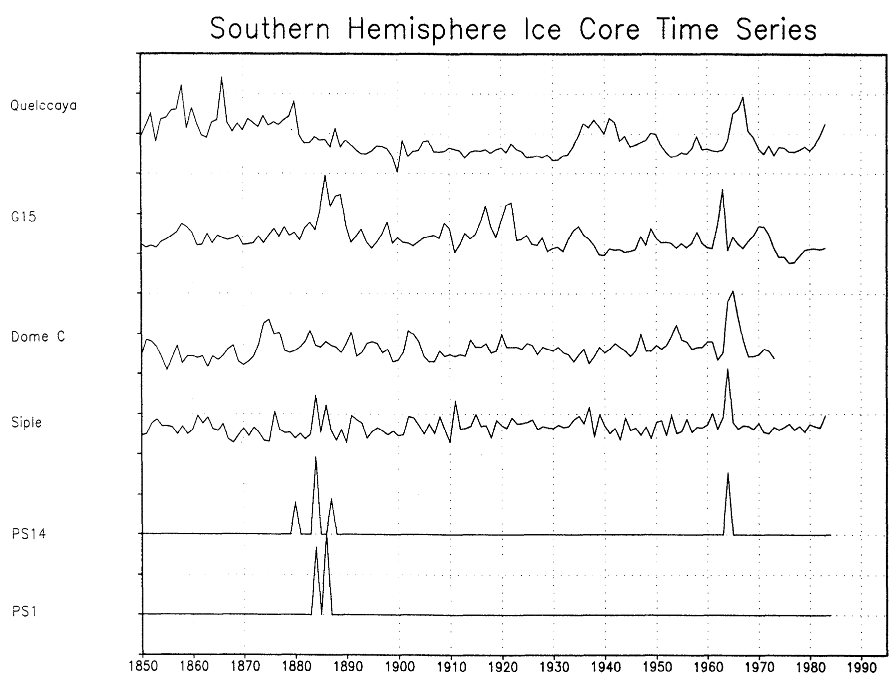

Figure 4. Southern hemisphere ice core time series. The PS1 and PS14 records were given only as peaks. See Table 2 for details about each series and units. All curves were adjusted to the same standard deviations.

Results for Dome C are particularly suspect because no absolute dating exists for that core. The investigators identified Krakatau with a peak dated in the 1870s rather than the 1880s, indicating that some dates in the Dome C record are as much as a decade in error [*Legrand and Delmas*, 1987]. Of course, using ECM or sulfate peaks as markers would artificially improve correspondence between cores in our analysis.

Another problem relating to dating is the variable time between the actual eruption and the time of the deposition on the ice. Local volcanoes can produce virtually synchronous deposits, while distant tropical eruptions can produce deposits during the period between a few months and a few years after the eruption. Weather variability, particularly the phase of the quasi-biennial oscillation of the stratospheric circulation, can play an important role in determining this time lag [*Trepte and Hitchman*, 1992]. It may be possible to establish the actual time lag for past eruptions, if the eruption can be positively identified, by a combination of data analysis and modeling, but this has not yet been attempted. For smaller ice core peaks, it may be impossible to accomplish this, as it would not be possible a priori to associate the peak with a particular volcano, unless associated tephra in the ice core could be analyzed and identified.

Another problem relating to time is the result of annual averaging. Input from a particular volcano can occur entirely in 1 year, or be spread out over 2 or even 3 years, thus introducing a possible factor of 2 variation in peak size for the same total deposition, or even the elimination of the peak from the record, if the values resulting from spreading the signal over more than 1 year are not large enough to be detectable.

These dating problems undoubtedly have some negative effect on the poor correlations among ice core records as seen below but cannot be the primary source of discrepancies. The intervals between successive large peaks vary so widely between cores that no simple realignment is likely to make them consistent. To attempt to partially correct for possible dating errors, we calculated correlations between each pair of time series with lags from -3 to +3 years, as described below. We did not have enough information to adjust the timescale within any individual time series.

Local Volcanoes (From the Troposphere to the Ice)

Eruptions close to the ice sheets can produce large sulfate deposits, even if no sulfate reaches the stratosphere and the volcanic eruption has no significant global effect. This seems to have happened most often with Icelandic volcanoes and the Greenland ice cores, but there are volcanoes on Antarctica, too, and the Antarctic eruption history is less well known. Again, detailed multivariate analysis of each deposit, including tephra characteristic of a particular volcano, may be able to identify each sulfate layer that is from a local volcano, if that volcano can be identified, but such analysis is very time consuming and that information is not available for most of these cores. Even hemispherically or globally important eruptions at latitudes near the ice cores, such as the 1912 Katmai eruption, can produce immediate deposition through tropospheric transport and later deposition after stratospheric residence, further complicating the dating and quantitative analyses.

From the Stratosphere to the Ice

The relationship between atmospheric aerosol loading and the amount of sulfate deposited in snow is not well understood, nor are transport patterns of these aerosols from their sources to the ice sheets reliably modeled. The mechanisms of stratosphere to troposphere exchange and the location and timing of these exchanges will affect the sulfate loading of the troposphere, and this may be different for each volcanic eruption, due to the timing, altitude, and latitude of the stratospheric injection and due to natural synoptic variability. As mentioned above, nonvolcanic sulfate sources also have their own variability, and so the background and volcanic components may cancel or amplify each other.

Stochastic Nature of Snowfall and Dry Deposition

Once the sulfates are in the troposphere in the vicinity of the ice sheets, they reach the surface either by dry deposition or by snowfall. Both of these processes vary strongly in time and space. *Zielinski et al.* [1992] found that in eight snow pits dug across Greenland, the El Chichón signal was strong in some of them and missing in others. *Jaffrezo et al.* [1994] also found that the accumulation rates and concentrations of ions can vary by a factor of 2 over spatial scales of a few hundred meters. This is a likely explanation for the low correlations we found between sulfate levels in ice cores from the same regions, as shown below.

In addition, because of synoptic and climatic variability the snowfall rate itself can change dramatically from year to year and even from decade to decade [*Steig et al.*, 1994]. The accumulation record has been analyzed for the GISP2 core [*Meese et al.*, 1994] but not for most other cores. Since the volcanic signal depends on the concentration of sulfate in the ice, whether measured as acidity or directly as sulfate, the strength of the signal can change over time if the snowfall rate changes, even if the sulfate amount stays the same. This variability would tend to introduce problems in comparing one volcanic eruption to another, rather than comparing ice cores for the same eruption in nearby locations, although it can also cause problems in comparing the same volcanic signal seen in different ice sheets. It will also introduce dating errors in regions of low annual accumulations, as discussed above.

Mixing Due to Blowing Snow

Once the sulfate has reached the surface, either in or mixed with snow, mixing of snow on the surface by wind adds further noise to the sulfate signal [*Fisher et al.*, 1985]. This factor may be combined with the variable deposition to explain the results of *Zielinski et al.* [1992] and *Jaffrezo et al.* [1994] above.

Temperature Dependence of ECM Measurements

Taylor et al. [1992] have pointed out that ECM measurements depend strongly on the temperature at which the measurements are made. This is probably because as the electrodes touch the ice, they melt a small amount that improves the electrical contact and increases the current, and the amount of melting also depends on the temperature. Therefore if different parts of the same core are measured at different temperatures in the field, the relative ECM values can differ, even with no change in acidity. Therefore although the peaks are preserved relative to the local background, the relative amplitude of the peaks at different parts of a core, or between different cores, is subject to temperature variations. This may explain part of the variations in the background ECM level found by *Crowley et al.* [1993] for the Crête core. *Taylor et* *al.* [1992] also pointed out that ECM measurements have a strong dependence on the voltage used, and since different groups have used different voltages, this factor must be considered when comparing different cores, but not peaks within the same core.

Comparison of Ice Cores and Nonglaciological Indices

Statistical Procedures

To compare the volcanic indices and ice core time series with each other, we needed to convert them to equivalent units and to isolate the volcanic from the background signals. In the case of the indices for all the cases the background level was 0, so we adjusted them to equivalent optical depth (τ) at λ = 0.55 μm, normalized to the values of *Sato et al.* [1993] for Krakatau in 1883. Since this is the largest eruption seen in both hemispheres in all indices, we simply adjusted all the time series to have the same value of τ as Sato et al. for the largest peak in the time period from 1880 to 1885. Although S. S. Khmelevtsov et al. (personal communication, 1993) expressed their index as a broadband τ over the entire visible spectrum, given that they do not have detailed information about the evolution of the size distribution and other optical properties during the lifetime of each aerosol cloud, the small differences will be negligible compared to the other differences in the indices.

For the ice cores, as can be seen in Figures 3 and 4 and as discussed by *Crowley et al.* [1993] for the Crête record, the main problem is the variable nature of the background, especially the large increase during the past century in the NH due to anthropogenic emissions. This background change is not linear or even the same for all ice cores, so we adopted the following procedure for removing the trends and isolating the peaks. We first removed the low-frequency variations from each time series with a Lanczos filter [*Duchon*, 1979] set to remove signals with periods longer than 10 years. This removes the trends and the variable background, allowing us to focus on the peaks. Next, we calculated the standard deviation (σ). Then we identified each potential volcanic peak by choosing each peak that exceeded the average of the previous 3 years by 2σ and was followed in one of the next 3 years by a decrease of 2σ. If the previous year was a peak, then we compared the current year to the years before that peak. This procedure is similar to those of *Mayewski et al.* [1993b], *Crowley et al.* [1993], and *Zielinski et al.* [1994]. Since the original calculation of σ included the volcanic peaks, we removed the years with the peaks and recalculated a background σ and then repeated the procedure with the new σ as a criterion for identifying the peaks. The resulting NH ice core peaks are shown in Figure 5 and the SH values are shown in Figure 6.

For each hemisphere we calculated correlation coefficients and their statistical significance, accounting for the autocorrelation in each time series [*Cook and Jacoby*, 1977] for the time series of ice core peaks (eight NH, six SH) and the five indices of volcanic activity. We used the maximum possible number of years common to each pair of time series. To partially account for the dating problems, we adjusted each time series forward and backward in time by 1 year at a time up to lags -3 and +3 years and redid each of the calculations to find the lag that gave the highest correlation with most of the other time series in that hemisphere. The results, along with visual inspection of the graphs of the series, suggested that DVI was 1 year ahead of the other indices. This is because Lamb assigned the largest value of DVI to the year of the eruption, independent of the month of the eruption and the time it took for stratospheric aerosol formation, while the other indices accounted for this lag. Several ice core records were 1 to 2 years out of alignment with the other records. We therefore ad-

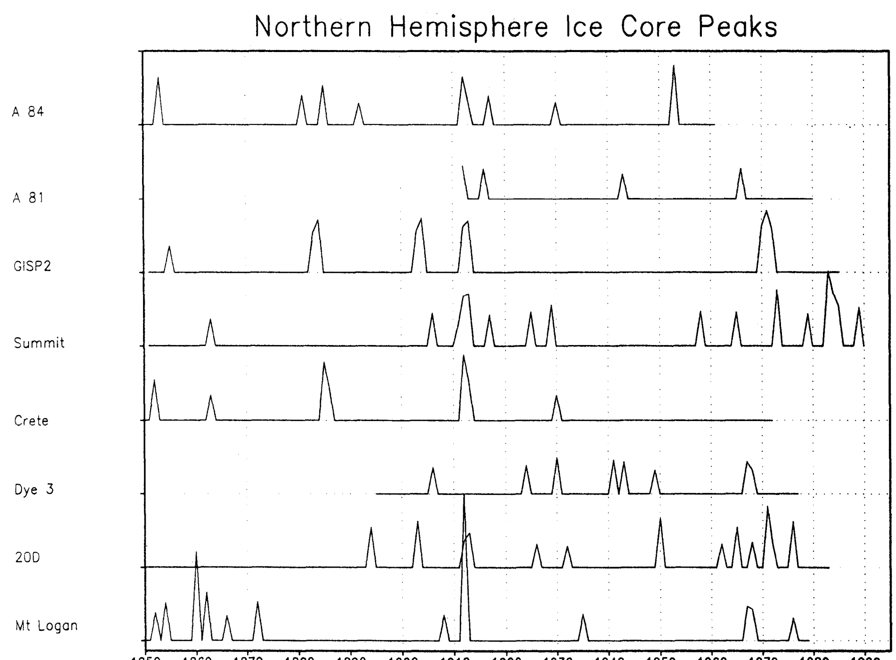

Figure 5. Northern hemisphere ice core peaks, after normalizing, removing long-term variations, and adjusting timing. See text for details and Figure 3 for original ice cores. Units are standard deviations. Tick marks and zero levels of the curves are 7 standard deviation units apart.

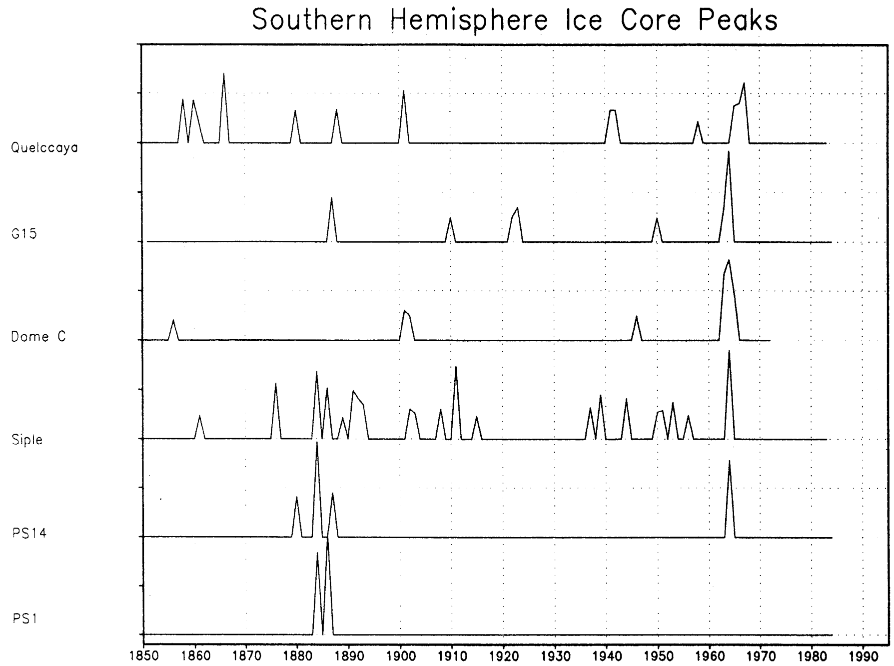

Figure 6. Southern hemisphere ice core peaks, after normalizing, removing long-term variations, and adjusting timing. See text for details and Figure 4 for original ice cores. Units are standard deviations. Zero levels of the curves are 10 standard deviation units apart. Tick marks and grid lines are 5 standard deviation units apart.

justed four of the ice core series forward or backward. For G15 the lag of 1 year is consistent with the dating convention (J. C. Moore, personal communication, 1994) and should not be considered an error. The required lags are indicated in Tables 1 and 2. The correlations are shown in Figure 7 for the NH and Figure 8 for the SH.

Discussion

Comparison of indices with each other. All the volcanic indices (Figures 1-2, 9-10) are significantly correlated with each other (Figures 7 and 8, section A). This is not very surprising, as all derive information about volcanoes from the

BOLD = SIGNIFICANT AT THE 1% LEVEL

ITALICS, UNDERLINED = SIGNIFICANT AT THE 5% LEVEL

	DVI	MITCH	VEI	SATO	KHM	A84	A81	GISP2	Summit	Crête	Dye 3	20D	Logan	IVI	NH T	SOI
DVI	**1.00**															
MITCH	**0.63**	**1.00**														
VEI	**0.37**	**0.64**	**1.00**													
SATO	**0.76**	**0.76**	**0.57**	**1.00**												
KHM	**0.57**	**0.81**	**0.68**	**0.68**	**1.00**											
A84	0.04	0.07	**0.31**	**0.29**	0.17	**1.00**										
A81	0.08	0.07	**0.32**	**0.38**	0.15	*0.31*	**1.00**									
GISP2	0.20	**0.44**	**0.65**	**0.31**	**0.35**	*0.20*	0.18	**1.00**								
Summit	*0.21*	0.05	**0.27**	0.19	0.15	**0.31**	0.15	0.12	**1.00**							
Crête	*0.25*	0.13	**0.51**	**0.52**	**0.32**	**0.50**	**0.43**	*0.24*	**0.41**	**1.00**						
Dye 3	0.00	-0.06	-0.09	0.00	-0.09	0.05	0.09	-0.10	-0.02	0.08	**1.00**					
20D	0.02	0.08	**0.32**	0.11	0.10	0.14	0.04	**0.44**	0.14	0.16	-0.06	**1.00**				
Logan	-0.01	0.00	**0.32**	0.14	0.05	**0.27**	**0.50**	0.17	0.22	**0.44**	0.08	0.15	**1.00**			
IVI	**0.28**	*0.22*	**0.55**	**0.40**	**0.28**	**0.60**	**0.47**	**0.49**	**0.65**	**0.71**	0.18	**0.48**	**0.70**	**1.00**		
IVI*						**0.44**	**0.38**	**0.29**	**0.47**	**0.59**	0.02	**0.29**	**0.44**			
NH T	-0.13	*-0.25*	**-0.26**	*-0.20*	**-0.33**	-0.04	-0.11	*-0.23*	-0.14	-0.15	0.01	*-0.21*	-0.12	**-0.26**	**1.00**	
SOI	-0.18	-0.11	-0.15	-0.18	-0.10	-0.09	-0.15	-0.01	-0.16	-0.18	-0.13	-0.13	-0.10	-0.17	0.00	**1.00**

IVI* is IVI calculated excluding the time series with which it is correlated.

Figure 7. Correlation coefficients between volcanic indices, ice core peaks, IVI, hemispheric average surface temperature and the Southern Oscillation index for the northern hemisphere. See text and Tables 1 and 2 for details.

	DVI	MITCH	VEI	SATO	KHM	Quelc	G15	Dome C	Siple	PS14	PS1	IVI	SH T	SOI
DVI	**1.00**													
MITCH	**0.61**	**1.00**												
VEI	**0.54**	**0.90**	**1.00**											
SATO	**0.66**	**0.72**	**0.56**	**1.00**										
KHM	**0.61**	**0.70**	**0.61**	**0.75**	**1.00**									
Quelc	0.01	-0.04	-0.06	0.00	0.02	**1.00**								
G15	0.16	0.13	0.00	**0.36**	*0.26*	-0.06	**1.00**							
Dome C	0.09	0.21	-0.03	**0.46**	*0.31*	0.11	**0.63**	**1.00**						
Siple	**0.24**	**0.30**	**0.27**	**0.27**	**0.37**	-0.10	**0.31**	**0.26**	**1.00**					
PS14	**0.47**	**0.50**	**0.41**	**0.43**	**0.64**	0.01	**0.53**	**0.34**	**0.46**	**1.00**				
PS1	**0.51**	**0.48**	**0.46**	**0.41**	**0.57**	-0.04	-0.03	-0.03	**0.39**	**0.43**	**1.00**			
IVI	**0.42**	**0.47**	**0.34**	**0.54**	**0.63**	-0.03	**0.67**	**0.60**	**0.78**	**0.80**	**0.54**	**1.00**		
IVI*							**0.50**	**0.40**	**0.52**	**0.65**	**0.30**			
SH T	-0.12	-0.16	-0.14	-0.07	-0.08	-0.09	-0.12	-0.04	-0.05	*-0.18*	0.05	-0.10	**1.00**	
SOI	-0.15	-0.09	-0.04	-0.17	-0.11	-0.10	0.10	0.02	0.10	0.04	-0.07	0.06	0.00	**1.00**

A **B** **C** **D**

BOLD = SIGNIFICANT AT THE 1% LEVEL

ITALICS, UNDERLINED = SIGNIFICANT AT THE 5% LEVEL

IVI* is IVI calculated excluding the time series with which it is correlated.

Figure 8. Same as Figure 7, but for southern hemisphere.

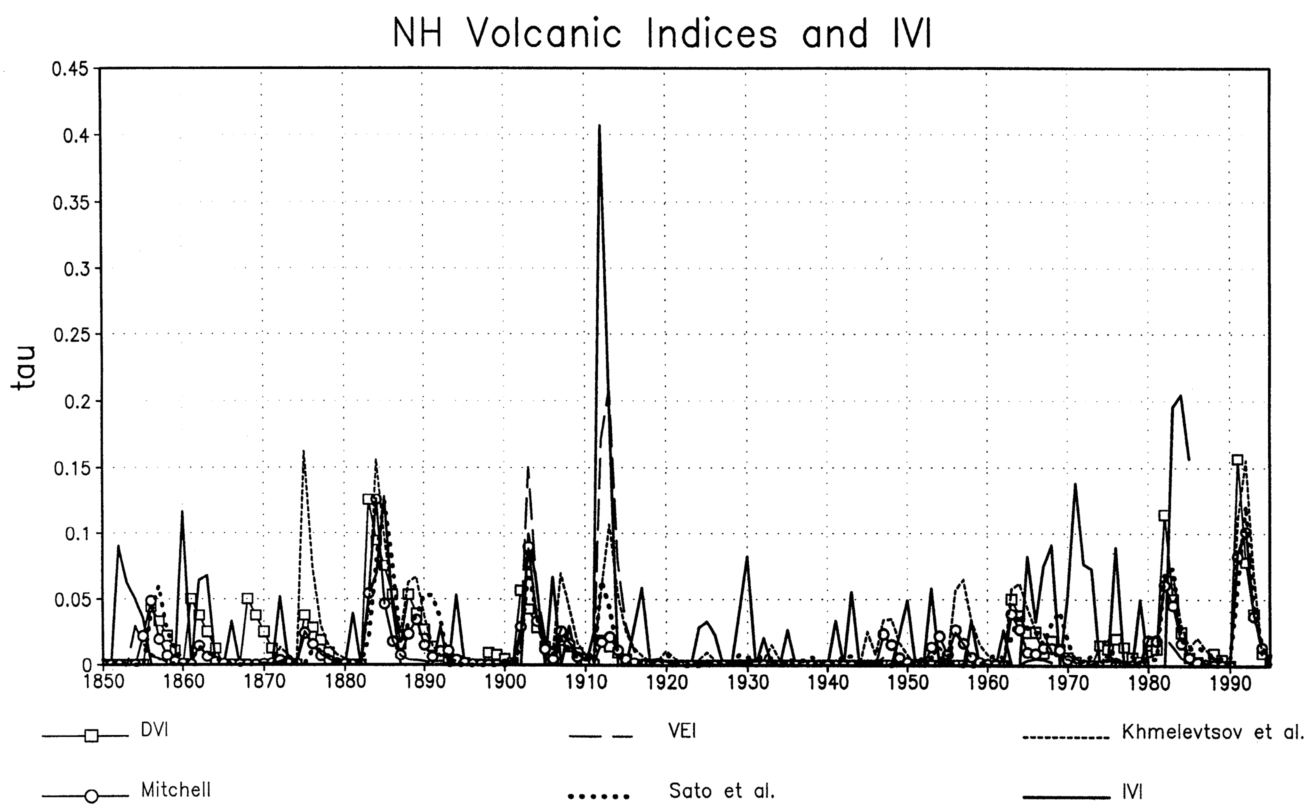

Figure 9. Northern hemisphere ice core-volcano index (average of eight ice core peaks shown in Figure 5) compared to volcanic indices (Figure 1), expressed as optical depth (τ) at $\lambda = 0.55$ μm, with all (including IVI) but KHM normalized to the values of SATO for the Krakatau peak in the mid-1880s.

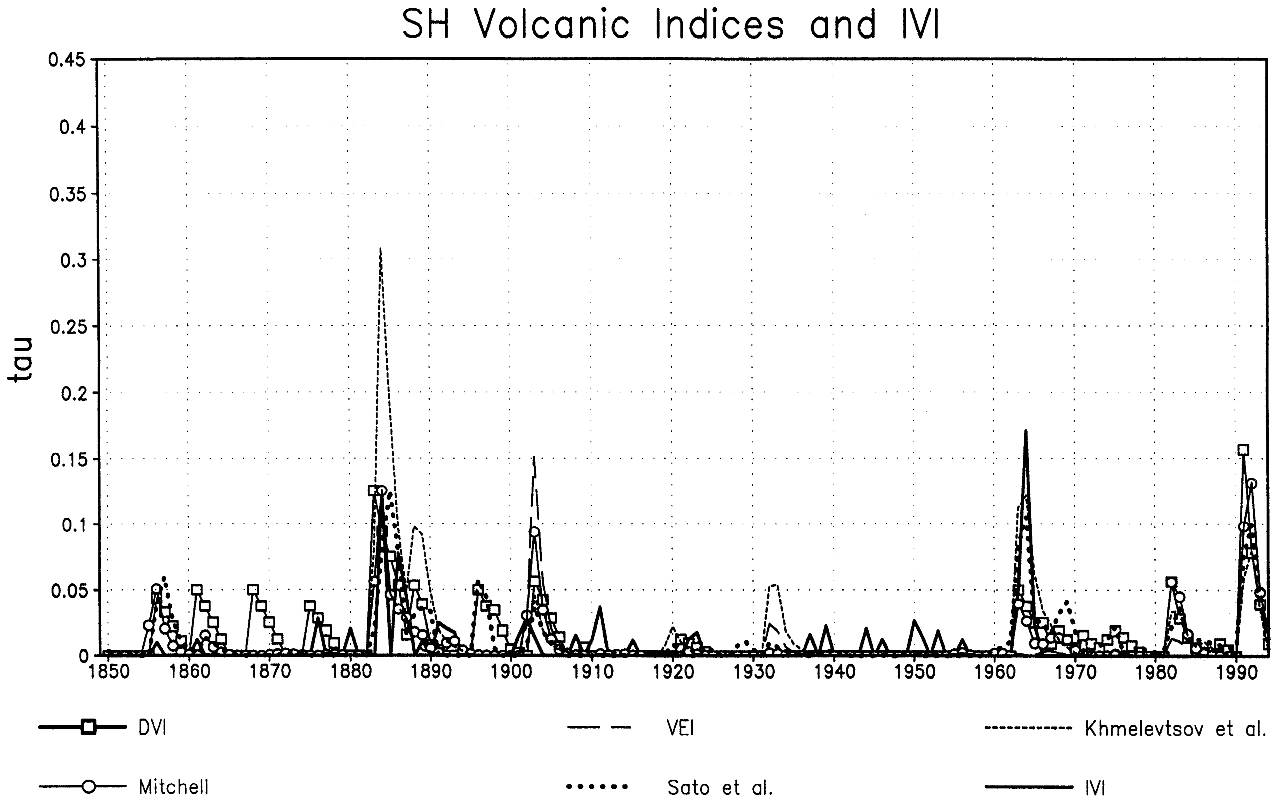

Figure 10. Southern hemisphere ice core-volcano index (average of 5 ice core peaks shown in Figure 6, excluding Quelccaya) compared to volcanic indices (Figure 2), expressed as optical depth (τ) at $\lambda = 0.55$ μm, with all (including IVI) but KHM normalized to the values of SATO for the Krakatau peak in the mid-1880s.

same historic sources, although in each one different interpretations are made of the evidence. As can be seen from Figures 1-2 and 9-10, even the VEI seems to correspond fairly well to the other indices, in spite of its well-known problems, but its correlations are slightly lower than the other indices. The VEI has a higher peak for the 1902 Santa Maria eruption (SH) and for the 1912 Katmai eruption (NH), and lower peaks for the 1963 Agung and 1982 El Chichón eruptions for both hemispheres, as compared to the other indices (Figures 1-2). It is difficult to tell by just examining the indices and their similarities and differences, which, if any, is a superior index.

Comparison of ice cores with each other. If the volcanic signal in ice cores were the dominant signal, one would expect these signals to be obvious in the ice core record and to correspond to each other in the different ice cores. This is clearly not the case for the ice cores in either hemisphere (Figures 3-4). In both hemispheres the interannual noise and trends obscure all but the largest peaks (Katmai in the NH and Krakatau and Agung in the SH).

In the NH (Figure 3), all the Greenland cores, with the exception of Crête and GISP2, show an upward trend due to anthropogenic sulfates and a relative minimum during the Depression of the 1930s can even be seen by those with excellent vision. (The GISP2 data set we received had already been detrended, but we do not understand the lack of a trend at Crête.) The Mount Logan core has a small upward trend after 1940. Mount Logan is so remote from the North American and European sources of pollution, because of its altitude and horizontal location, that most anthropogenic aerosols are removed from the troposphere before reaching the ice. Perhaps it is a better record of Asian anthropogenic pollution. The Ellesmere cores do not show a simple trend. They both show decreases from the 1910s through the 1950s, which would have to be explained by changes in the circulation patterns in that region that are more important than distant sources.

The peaks of the NH cores (Figure 5) do not correspond, with the exception of one around 1912, which is from the Katmai (Novarupta) eruption in the Alaskan peninsula. Since the Katmai eruption (58°N) was at about the same latitude as the ice cores, much of the sulfate in the cores may be from immediate tropospheric transport and not representative of hemispheric-average stratospheric loading. The Mount Logan site is the closest to Katmai and also shows the highest value over the background, as compared to the other cores, supporting this speculation.

Figure 7 (section B) shows the correlations between the ice core peaks. Although almost all are positive, only 11 of 28 pairs of correlations are significant. A84 and Crête are the most highly correlated with other cores, but nearby cores (A84 and A81, GISP2, and Summit) have much lower correlations than distant ones. Thus it is not possible to identify any individual ice core that would be representative of hemispheric-average volcanism. Even cores drilled 2 m apart, opposite sides of the same core, and measurements from the same side of the same core before and after longitudinal cutting exhibit a substantial amount of high frequency disagreements [*Fisher and Koerner*, 1994; *Fisher et al.*, 1995, D. A. Fisher, personal communication, 1994].

The SH cores (Figure 4) do not show the same upward trend as in the NH, and Quelccaya shows large low-frequency variations, which are related to episodes of alkaline dust transport [*Thompson et al.*, 1988]. The Quelccaya record, from the tropics, does not resemble the Antarctic records, except for what may be an Agung signal in the late 1960s. However, we would expect a tropical signal from a tropical volcano to begin earlier than the high-latitude signal, and it does not. Because of the agreement of the peaks (Figure 6) on Krakatau and Agung, the Antarctic ice cores are all similar and well correlated (Figure 8, section B).

Comparison of ice cores with volcanic indices. Only one of the NH volcanic indices (VEI) is correlated with most of the NH ice cores (Figure 7, section C). This is because the high-latitude 1912 Katmai eruption had a very high VEI and it is the most prominent peak in the ice cores. As discussed above, this does not mean that either the VEI or the ice core records are representative of the entire NH. The Sato index is significantly correlated with half of the ice cores but not the others.

Most of the SH ice core records are well correlated with the SH indices (Figure 8, section C), because of the agreement on Krakatau and Agung.

Composite ice core-volcano index (IVI). In an attempt to remove the random component of the signal in the ice cores, we averaged all the ice core peaks in each hemisphere together and also show these averages in Figures 7-12. For the NH we used all eight cores. We considered giving Mount Logan more weight than the other cores, as it is the only one from the Pacific region. However, the cores from Greenland show as large disagreements among themselves as they do with Mount Logan, so we were not sure how representative Mount Logan was of a large region. For the SH we used the five cores from Antarctica but did not include Quelccaya. We have named this new index, one for each hemisphere, the ice core-volcano index (IVI).

We also considered creating a glaciological volcanic index [*Legrand and Delmas*, 1987] by weighting each eruption according to its latitude, to account for the fraction of each stratospheric aerosol veil that was recorded in each ice core. In addition, we considered using the method of *Langway et al.* [1988] to use results from nuclear-bomb tests to weight the various eruptions based on their latitude. Both of these proved to be impossible, because each ice core showed different peaks, and we were not able to unambiguously identify each peak with a particular eruption. For the largest peaks in each hemisphere (from the 1912 Katmai (Novarupta) eruption in the NH, and from the 1883 Krakatau and 1963 Agung eruptions in the SH) this would be easy, but there are many other peaks for which it would not be.

Figures 9 and 10 show the IVIs compared to the volcanic indices for each hemisphere, and Figure 11 shows the IVIs compared to each other. Section D of Figures 7 and 8 shows that these averages are highly-correlated with all the indices and all high-latitude ice cores in each hemisphere, except the short Dye 3 record, which does not have a Katmai peak. The correlations with the individual ice cores are higher than any correlation of any ice core with another core, except for the short record of A81 and Summit with Crête, where they are about equal.

Of course, by including all ice cores in the IVI, we guarantee a certain amount of correlation of IVI with each of the cores used in its construction. Therefore as was done by *Bradley and Jones* [1993] for climatic time series, we calculated new versions of IVI (IVI*) by excluding one core at a time and recalculated the correlation with each excluded core. As seen in Figures 7 and 8, each IVI* is still significantly correlated with all cores, although the correlation is slightly smaller than with IVI. These high correlations show that averaging has filtered out uncorrelated noise in each core, producing a better record of volcanism than any individual core.

Comparison of IVI with Temperature and ENSO Records

To examine the relationship of the volcanic record to two potential climatic effects, we looked at the relationship of the IVIs to temperature and ENSO records. For temperatures, we used the global surface temperature data set produced by the Climatic Research Unit of the University of East Anglia [*Jones et al.*, 1986a, b, c; *Jones*, 1988] and updated to include global surface air temperature observations over land and sea surface temperatures from ship observations [*Houghton et al.*, 1990; *Jones et al.*, 1991; *Jones and Briffa*, 1992]. The data set was kindly provided by Phil Jones and consists of monthly average temperature anomalies with respect to the mean for the period 1951-1980, the period of best data coverage. We calculated hemispheric annual averages from 1854 through 1992. The spatial coverage of the data set is incomplete and changes with time. Coverage in the NH is always greater than in the SH. The data from Antarctica are available only since 1957. We use high-pass Lanczos filtering [*Duchon*, 1979] to remove the low-frequency variations with periods longer than 10 years and removed the ENSO signal by linear regression on the Southern Oscillation index [*Ropelewski and Jones*, 1987], lagged by 6 months [*Jones*, 1988]. Because the peak of an ENSO event occurs at the end of the year, an annual average of the SOI calculated from July to June of the next year captures much more of the ENSO signal.

Figure 12 shows the IVIs compared to the temperature and ENSO records. The high-pass component of the NH temperature data, with the ENSO signal removed, is negatively correlated with the NH IVI, significant at the 1% level (Figure 7). All the indices and ice cores are also negatively correlated with the temperature, but the average is more highly correlated than all except KHM, which includes a large value for the 1875 Askja eruption, corresponding to a cooling. The SH IVI was not significantly correlated with the temperature data.

We also calculated correlation coefficients between the ice core and the volcanic index time series and the Southern Oscillation index and found no significant correlations (Figures 7-8, 12). Thus our work provides no support for the idea that volcanoes produce ENSO warm events.

Discussion and Conclusions

We present this section in the form of questions and answers. This work, while not completely answering all these questions, does provide additional information about each of them.

How much information about hemispheric-average stratospheric volcanic aerosol loading is provided by currently available ice core analyses? There is definitely a volcanic signal in the currently available ice cores, but for each core, it is mixed with many other nonvolcanic signals. By isolating the peaks and then averaging them to produce the IVI, we feel that we have reduced the noise enough to see a volcano signal.

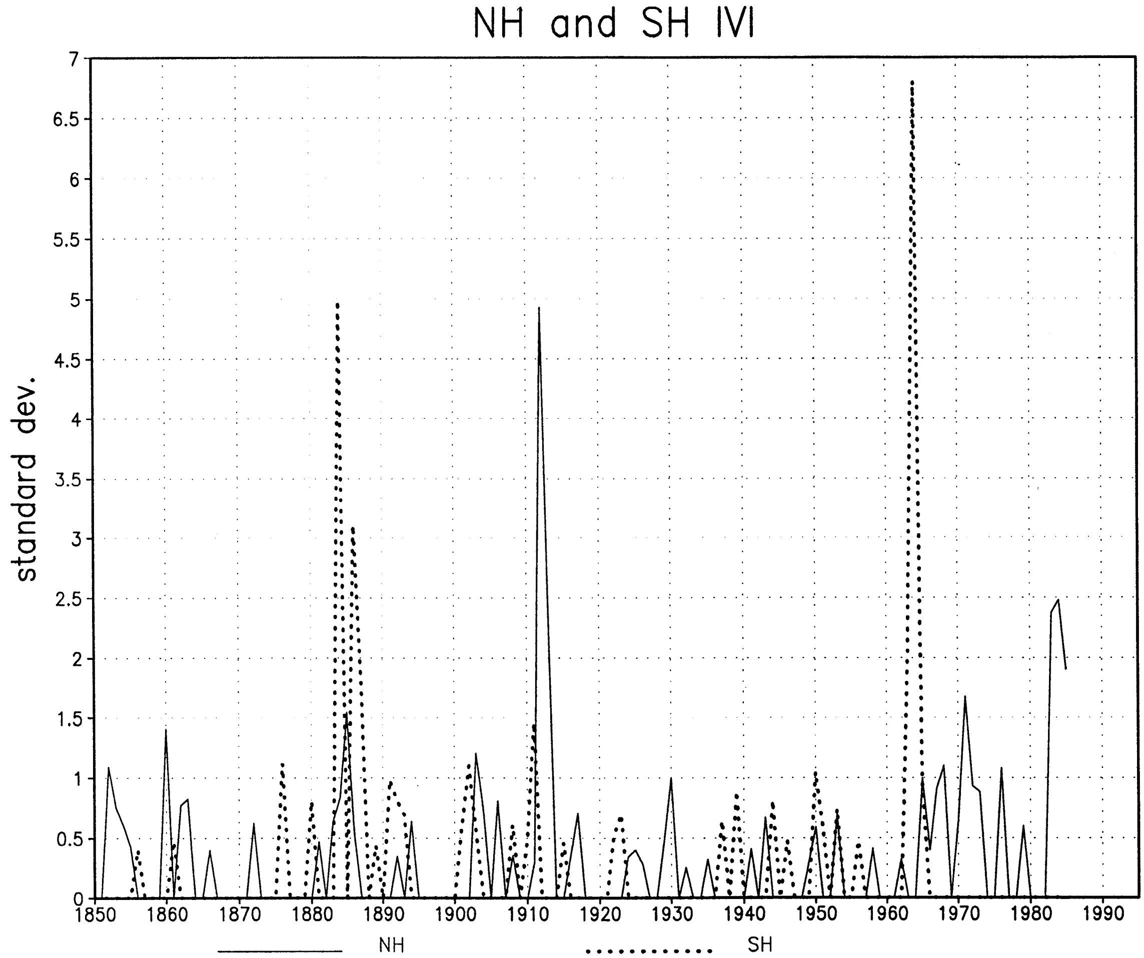

Figure 11. Northern hemisphere and southern hemisphere IVI compared to each other. Units are standard deviations.

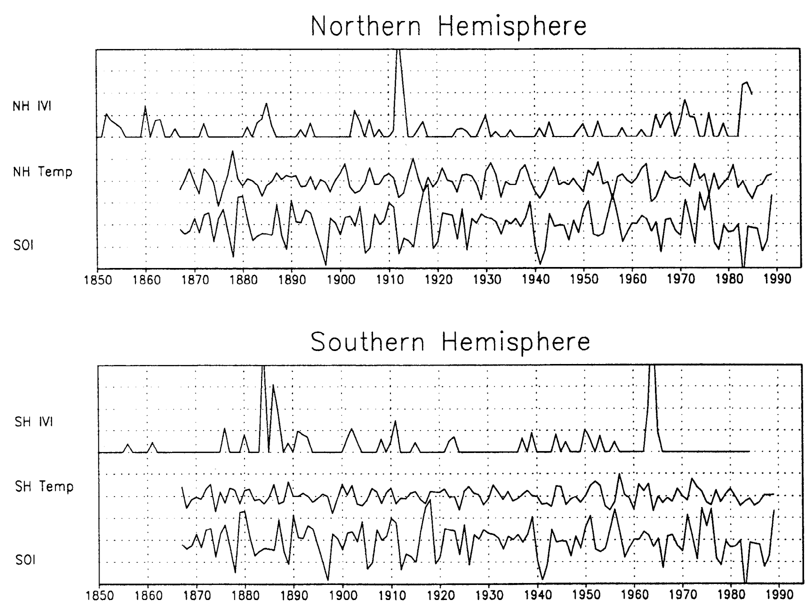

Figure 12. Northern hemisphere and southern hemisphere IVI compared to high-frequency temperature records for each hemisphere with the ENSO signal removed and to the 6-month lagged Southern Oscillation index (SOI). Tick marks and grid lines are 1 standard deviation apart for IVI and SOI and 0.1°C apart for the temperature curves.

For volcanic eruptions which we can identify, certain problems are obvious. The 1912 Katmai eruption shows the largest signal in all the NH ice cores and in the NH IVI. Although this was clearly a large eruption, we cannot use ice core evidence to quantitatively adjust the hemispheric index to account for its relative size, as compared to the other peaks. In the first place, we cannot reliably quantify the tropospheric-stratospheric partitioning that occurred and so cannot know how much of the Katmai signal is representative of stratospheric input, although geological evidence points to this eruption being mostly stratospheric, with probably only Mount Logan having significant tropospheric aerosols. The second highest peak in the NH IVI is in 1982 and 1983, corresponding to the 1982 tropical El Chichón eruption, but it appears in only 1 of 3 available cores for that recent time. The third largest peak is in 1971, corresponding to the tiny 1970 Hekla eruption, appearing in 4 of 5 of the Greenland cores but not in the Ellesmere or Mount Logan cores, showing that a small local eruption can produce a large signal in the average. If we could unambiguously identify every peak in every core, we could eliminate such peaks with local tropospheric input, but that is not possible now. With a better geological database, now under preparation, we may be able to address this issue in the future.

In addition, we do not know how to compare the relative inputs from volcanoes at different latitudes. Estimates from ice core measurements of fallout from two cases of stratospheric injections from nuclear bomb tests [*Langway, et al.*, 1988] provide a rough estimate but may not be representative of latitudinal mixing in other cases. Furthermore, as discussed above, for many of the other peaks we cannot unambiguously identify the responsible volcanic eruption.

For identifiable tropical eruptions the ice core evidence tells us a little about the relative hemispheric partitioning of the aerosol clouds. We cannot rely on the relative size of the peaks in Figure 11 to compare between hemispheres, as the peaks are in standard deviation units and depend on not only the amount of sulfate deposition in the peaks but also the size of the background noise. We can see, however, that the 1883 Krakatau eruption produced large peaks in both hemispheres, while the 1963 Agung eruption, from exactly the same latitude at the other end of Java, produced a much larger peak in the SH but a much smaller peak, if any, in the NH. The 1902 Santa Maria eruption (combined with two smaller ones) produced similar size peaks in both hemispheres.

Still, several of the problems discussed above remain. Approaches to solve some of these problems are presented below.

How well do available volcanic indices represent the stratospheric loading? All of the indices seem to capture some of the variance of the ice core record. Sato et al. and Khmelevtsov et al., taking advantage of recent measurements, partition the 1963 Agung signal in better agreement with the IVIs than the older records and produce a SH index in better agreement with the ice cores. For the NH the picture is not so clear. The 1912 Katmai eruption dominates the ice core signals and is given greatest weight in the VEI index construction, and the VEI shows the best agreement with the ice cores. The Sato et al. index produces the second highest agreement. The ice core evidence is not conclusive enough or in good enough agreement to further categorize the quality of these indices.

Are some ice cores better than others at representing the volcanic signal? In general, higher elevations and more remote locations should experience less nonvolcanic aerosol than other areas. Thus some locations may provide a better volcanic record than others. One would expect central Greenland, where the Crête, Summit, and GISP2 cores were drilled, to be better than other Arctic locations because of its high elevation and greater distance from the ocean [*Clausen and Langway*, 1989]. However, our correlations and visual comparison of the time series do not show greater correspondence among cores from central Greenland than between those cores and cores from other locations. The lack of resemblance between the GISP2 and the Summit records is particularly surprising since both are recent measurements of sulfate from high-altitude locations quite close to each other. These results suggest that differences between regions are not the primary cause of the poor correlations among cores. The need for more cores to improve the signal to noise ratio in the average is evident.

Are sulfate records better than ECM measurements? Since acidity records and sulfate records measure different quantities, some of the low correlations among ice core series may be attributable to the use of different techniques. If measurement type were a critical factor in the low correlations, one would expect newer measurements to correlate better than older measurements and sulfate concentration data to be better than conductivity data. However, the sulfate records in this study do not, in general, show better correlations with one another or with the volcanic aerosol indices than do the acidity measurements. One of the ice core records with the best correlations with the non-ice-core indices is Crête, a very early conductivity measurement. Our comparisons therefore do not support the hypothesis that measurement type is a critical factor in the accuracy and reliability of ice core volcanic records.

Can ice cores be used to give a continuous record of relative volcanic forcing, or only to identify particular eruptions that may be important? We have focused in this study on hemispheric-average, annual-average records of the stratospheric aerosol loading produced by volcanic eruptions and their climatic impact. We did this because we are constrained by the locations and temporal resolution of the ice core records. The radiative and dynamical forcing of stratospheric aerosol clouds is strongly dependent on their latitudinal and seasonal distributions [*Graf et al.*, 1993; *Robock and Mao*, 1995]. Therefore an ideal record of past volcanism would resemble the format of the *Sato et al.* [1993] archive, which provides monthly average optical depth as a function of latitude. In addition, the time evolution of the microphysical characteristics of the volcanic aerosols, including ash as well as H_2SO_4, strongly affects their radiative impact, and the optical depth at $\lambda = 0.55$ µm, as presented by Sato et al., does not provide enough information to calculate the entire climatic forcing. Therefore rather than use an index like the IVI, or the other indices studied here, a superior approach in future work would be to use the IVI to identify climatically important eruptions and then use models to calculate the evolution of the microphysical characteristics and location of the aerosols. As seen with the three recent tropical eruptions, Agung in 1963, El Chichón in 1982, and Pinatubo in 1991, the partitioning of the aerosol as a function of latitude strongly depends on the prevailing atmospheric circulation. We cannot know these initial conditions for past eruptions, but can constrain our models by examining the NH to SH IVI ratios, in a manner similar to *Langway et al.* [1988]. However, smaller or higher-latitude volcanic eruptions may not be analyzed with this approach, as their signal is not seen in the other hemisphere, but they can still be important climatically.

Is the new ice core-volcano index (IVI) a better measure of past climatically relevant volcanism? Extracting the volcanic signal from individual ice core records is complicated because of noise from other sulfate sources, because the volcanic signal itself is distorted by local variations in aerosol transport and precipitation, because of dating and measurement uncertainties, and because of the influence of aerosols from local volcanoes. As a result, no one ice core record is likely to be a reliable indicator of past volcanic aerosol loading. Our analysis technique reduced some of this noise. In spite of the noise problems and the existence of direct atmospheric transmission measurements for much of the twentieth century, an ice-core-based index may be a major improvement over existing volcanic indices for the period before satellite measurements, as ground-based and in situ measurements never assured global coverage. For periods before 1900, where direct information is scarce, an index based on a composite of ice core records should be superior to the existing indices of volcanic aerosol loading.

Our new index was the result of subjective decisions in its creation. For example, we considered only using peaks that occurred in two or more cores, because any individual peak may be nonvolcanic. NH and SH indices constructed in this way are shown in Figure 13 compared to the original IVI. While the curves resulting from this alternate method seem to be less noisy and more pleasing to the eye and correspond to our preconceptions of the shape of volcanic indices (see Figures 1-2), we do not have enough information at this time to tell whether it eliminated eruption signals that should have been left in. The correlations from this alternative were about the same as those shown in Figures 7 and 8, but the correlation with NH T was slightly lower at -0.21, significant at the 3% level.

What does this new information tell us about the effects of volcanoes on temperature variations? Our new volcanic index provides an independent, physically based measure of volcanic aerosol loading for comparison to temperature records. Our results give independent confirmation of the relationship of volcanic activity to short-term NH temperature variations since 1850, but the IVI may still be biased to high-latitude eruptions. For the SH, although almost all the correlations between T and all volcanic measures are negative, as expected, they are not significantly so. This may be due to the poor quality of SH temperature records combined with the fact that the SH is less responsive in the short-term to volcanic eruptions due to its much smaller fraction of land [*Robock and Liu*, 1994; *Robock and Mao*, 1995].

What does this new information tell us about the speculation that volcanoes can produce El Niños? Our work provides no evidence for a link between volcanic eruptions and El Niños. None of the volcanic indices or ice cores is correlated with the Southern Oscillation index, the best available record of past ENSO variations.

What additional analyses can help to more completely answer these questions? The analysis presented here could clearly be extended by including more ice cores from Greenland and Antarctica, to aid in the filtering of local noise, and more cores from underrepresented regions, such as northwestern North America and the tropics. In addition, simultaneous analyses of the acidity and the various chemical species [e.g., *Whitlow et al.*, 1992] can serve to provide a more complete picture of the volcanic input to ice cores.

Our work to date has been limited to the period 1850 to the present. This has been a period of relatively few large volcanic eruptions as compared to other periods in the recent past. Periods with more volcanoes would have allowed more cases with which to perform the above analysis. We plan to extend this work back 2000 years, when an improved volcanic

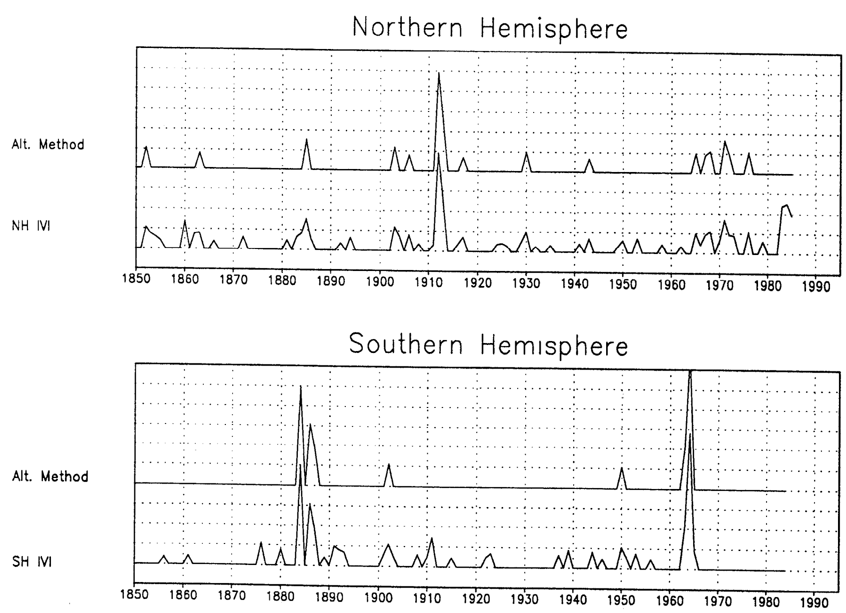

Figure 13. Northern hemisphere and southern hemisphere IVI compared to an alternate method of calculation, only including peaks that occur in two or more cores. Tick marks and grid lines are 1 standard deviation apart for all curves.

index could be important in analyzing the causes of episodes of cold temperatures, such as the little ice age.

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